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ESTUARINE POLLUTION PROBLEMS

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Technical Approaches Toward Evaluating Estuarine Pollution Problems

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Pollution caused by the discharge of pulp and paper mill wastes into marine waters at Everett, Bellingham, Anacortes, and Port Angeles, Washington, has stimulated field investigations which have been undertaken to support the enforcement proceedings authorized by the Federal Water Pollution Control Act. The programs include field research and investigations to determine the effects of such wastes on water quality, water uses, and the marine environment. The total effort represents cooperative participation by the U. S. Public Health Service; the Washington State Water Pollution Control, Fish, and Game Departments; universities; and industries.

Although the project was initiated in the spring of 1962, numerous technical problems and delays were encountered in tooling up for the job; it was about the same as starting with nothing and organizing miniature departments of oceanography, engineering, and biology and equipping them to function. The initial goal, to have all phases of the field program begin together and progress simultaneously, was unattainable. Therefore, additional sampling was necessary along the way to provide sufficient supporting information for each phase of study.

The program consists of several major elements—in-plant surveys, oceanographic studies, biological studies, and economic studies. The findings at Everett, Bellingham, and Port Angeles illustrate several aspects of the oceanographic and biological studies (Fig. 1).

NATURE OF THE OCEANOGRAPHIC STUDIES

The oceanographic studies have three principal objectives: (1) determining the dispersion and persistence of pulp mill wastes at the surface and at depths related to the flushing characteristics of the areas; (2) determining the extent and thickness of sludge beds caused by industry; and (3) determining the effect of surface waste concentrations on light penetration. Another important objective is to provide project biologists with the necessary physico-

chemical background on which to design their studies. Plankton, productivity, and larva bioassay sampling stations, for example, were selected on the basis of oceanographic field data. Temperature, salinity, dissolved oxygen (DO), Pearl-Benson Index (PBI), pH, and light penetration by Secchi disk were routinely measured on monthly field trips. Equipment is now being used which is more refined than the Secchi disk.

(The Pearl-Benson Index (PBI), as used in this paper, is the dilution of sulfite waste liquor (SWL) containing 10 percent solids expressed as ppm by volume; determined by the Barnes *et al.* (1963) modification of the Pearl and Benson (1940) technique. Although not synonymous, the terms PBI and SWL will be used interchangeably. The term "spent sulfite liquor" (SSL) is used by some and is equivalent to SWL. A model GS Beckman meter was used for pH; the Alsterberg (azide) modification of the Winkler method (A.P.H.A., 1960) for dissolved oxygen (DO) was used.)

The location and depth of sampling in all three areas were governed by the following concepts:

1. Stations were selected to allow adequate coverage of conditions from maximum sulfite waste liquor (SWL) concentration to those of little or no SWL. Stations were close enough together to allow contouring of the data and dispersed only enough to permit sampling a given area in one day.

2. Although SWL concentrations and associated effects at the surface are important to juvenile salmonids, concentrations in deeper waters are also important, especially at Everett, for their potential influence on: (a) sessile bottom fauna, (b) bottom fisheries, such as crab, flounder, and other demersal fishes, and (c) plankton.

3. In areas where only surface discharges are made, vertical mixing and diffusion will occur and, consequently, deeper waters must be sampled.

4. Pulp and paper mills usually operate around the clock, 12 months a year. There are seasonal and diurnal fluctuations of water properties throughout the water column, and the sampling was designed to obtain enough data to reflect at least one year of mill operation in each area.

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Fig. 1. Location map of Puget Sound area.

Oceanographic literature on Puget Sound and adjacent waters is voluminous, and no attempt is made to review it thoroughly here. The University of Washington (1953) has conducted long and extensive studies of Washington marine waters and has published a comprehensive literature review of the area. The Bellingham-Samish Bay system, in particular, has been investigated in regard to flushing characteristics and SWL distribution (Collins and Barnes, 1962). The University of Washington has also completed a study of Bellingham Bay currents using Richardson meters supplied by the U. S. Public Health Service. The Pacific Oceanographic Group in Canada has also conducted numerous surveys in the Strait of Juan de Fuca and contiguous waters.

Because of the information already available on the Bellingham-Samish system, most of the present oceanographic work has been carried out in Everett and Port Angeles. These two areas have been studied by agencies of the State of Washington (Lindsay *et al.*, 1960; Orlob *et al.*, 1951; Peterson and Gibbs, 1957). Some of the pulp and paper companies concerned also have conducted field studies, but the resulting data are not generally available. Stein *et al.* (1963) published a report showing conditions existing in the Port Angeles area during a two-week survey.

NATURE OF THE BIOLOGICAL STUDIES

The objectives of the biological program are to detect and measure the influences of pulp and paper mill

wastes on significant marine organisms and their environment. Such information will help to determine whether damages have been caused by pollution and, if so, to define the necessary remedial steps. Eight separate activities are involved in doing this, as shown in Table 1.

Other investigators have approached some of these objectives and a sizable literature has developed, especially relating to salmonids and shellfish (Lasater, 1954; Tollefson, 1963; Wagner *et al.*, 1957; Waldichuk, 1960). The toxic effects of SWL on young salmon have been studied intensely for several years. Mains *et al.* (1953), and Gunter and McKee (1960) thoroughly reviewed and evaluated current information on the effects of SWL on oysters.

Of the eight biological activities cited above, only three will be discussed in this paper: (1) oyster larva bioassays for the Bellingham-Samish and Port Angeles areas; (2) adult oyster mortality, growth, and condition index for the Bellingham-Samish area; and (3) live box bioassays with juvenile salmonids for the Everett area.

GROSS CHARACTERISTICS OF THE THREE AREAS

The three major areas under investigation have little in common, except that they are all bathed in salt water. Because Puget Sound itself is an estuary, waters adjacent to Everett may be considered an estuary within an estuary, since already dilute sea water at this point is freshened still more by entry of the Snohomish River. Bellingham Bay is similar, because it is fed at its northernmost end by the Nooksack River. Port Angeles harbor is not a true estuary, according to Pritchard's (1955) definition, because no large streams enter it. Indeed, its low-salinity water in the surface layer is mostly due to wastes from pulp and paper mills along the harbor shores.

It is customary to classify estuaries by their vertical and lateral salinity gradients. Because salinity is a result of an estuary's geomorphology, tides, and run-offs, its distribution reveals more about the type of estuary than any other single factor. Therefore, "typical" salinity, PBI, pH, and DO concentrations compared with depth-station curves are all used to exhibit the gross characteristics of each of the three areas.

OBSERVATIONS IN THE BELLINGHAM AREA

OCEANOGRAPHIC

Because of the extensive surveys conducted by the University of Washington in the Bellingham-Samish Bay system, the U. S. Public Health Service oceanographic field work was confined to a study of summer conditions in Bellingham-Samish Bay (Fig. 2). Sea water enters the system at depth primarily between Guemes and Lummi Islands, and is about two to four

Table 1. Type, area, and frequency of biological investigations.

Type	Areas	Frequency of invest.	Initiation date
Vertical and horizontal tow collections of plankton	All	Monthly	July, 1963
Submerged microslides for attached organisms	Bellingham-Everett	10 days	Feb., 1964
Productivity and nutrient supply	Bellingham-Everett	Monthly	March, 1964
Adult oyster mortality, growth, and condition index—Phase 2	Bellingham-Samish	Monthly	March, 1964
Oyster larva bioassay	All	Monthly	May, 1963
Live box bioassay, juvenile salmonids	Bellingham, Port Angeles, Everett	Summer	April, 1963
Distribution-migration, juvenile salmonids	Bellingham, Port Angeles, Everett	Spring and Fall	March, 1963
Bottom fisheries, trawling	Bellingham-Samish, Port Angeles	Monthly	Dec., 1963

parts per thousand (‰) less saline than water in the Strait of Juan de Fuca near Port Angeles.

Figure 2 also shows that the 1960-1961 average surface PBI (Collias and Barnes, 1962) decreases with distance from the waste source, but extends as a detectable plume into Samish Bay. The percentage remaining with distance relative to the 200 parts per million (ppm) contour can be obtained by dividing

all values by two. Waters throughout the system are markedly turbid, with Secchi disk readings generally less than two meters. Low light transmission is caused by SWL, suspended fibers from the pulp and paper mill, plankton blooms, and silt transport from the Nooksack, Samish, and other smaller rivers. Effect of mill effluents in lowering DO levels is localized to within a one- to two-mile radius of the outfall, but oxygen saturation values of 120-140 percent are not uncommon in the upper 10 m during plankton blooms.

Figure 3 shows station curves at Stations A and B at two distances from the waste source. Station A, nearest the outfall, shows that PBI decreases rapidly with depth and is not found beneath the halocline. DO and pH are decreased in the upper 2 m. At a greater distance from the outfall, PBI values have diminished, and no effect on pH and DO is apparent. Surface salinity has also increased from 25.6 to 28.3 ‰ because of this station's position relative to the Nooksack River.

OYSTER STUDIES

Oyster culture was formerly one of the water uses in parts of Bellingham Bay, but it is now limited to the adjacent waters of Samish Bay. In that area, Pacific oysters (*Crassostrea gigas*) are cultivated from seed imported from Japan or Canada.

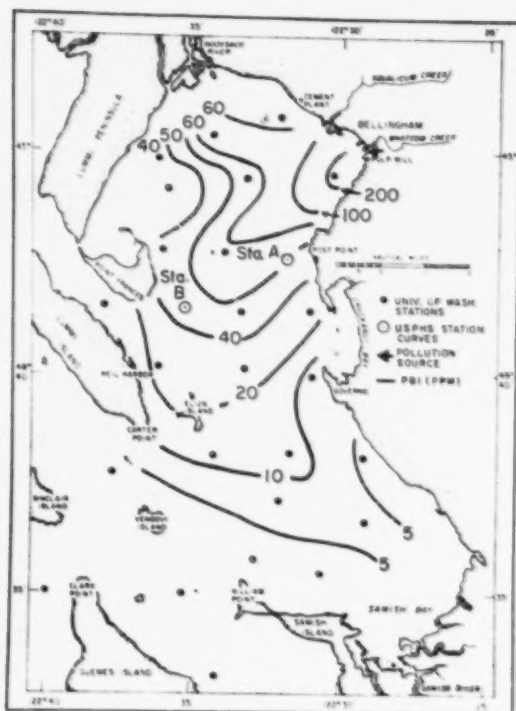


Fig. 2. Bellingham, Washington. Average surface Pearl-Benson Index (PBI) from University of Washington data (Collias and Barnes, 1962).

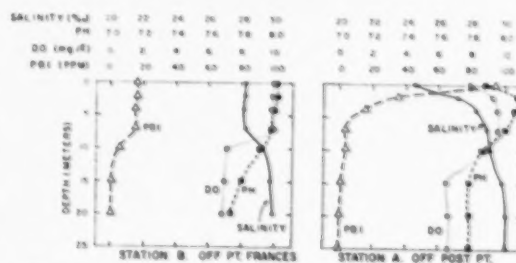


Fig. 3. Bellingham, Washington. Station curves, June 25, 1963.

Because wastes from the Bellingham mill are carried southward to the oyster-growing areas, it was necessary to devise a means of sensing the response of oysters to this factor of their environment. Two methods were developed: (1) larva bioassays of water samples were collected at key points in the area, and (2) *in situ* bioassays were made of one- and two-year-old specimens of seed oysters to determine growth, survival, and condition index or fatness.

Each month one surface-water sample is collected by seaplane at each of 11 sampling points (Fig. 4). The samples are flown directly to the Point Whitney laboratory of the State of Washington Department of Fisheries to be processed. The time lapse from collection to processing never exceeds three hours. The technique is described by Loosanoff (1954) and has been modified by Woelke (1961). In brief, Pacific oysters are stimulated to spawn by raising their temperature to 25°–30°C. for three hours after having been held for four to six weeks at 20°C. At one and one-half hours or less after fertilization, about 25,000 larvae are added to each sample. After a 48-hour exposure to the test water, a sample containing 100–200 larvae is examined microscopically to determine the percent of "abnormal" larvae (those which are not fully shelled). Analyses are made for initial and ter-

Table 2. Oyster larva bioassay data for Bellingham-Samish area. Summary for period, May 13 to November 20, 1963.

Station	Kilometers from pollution source	Number of cultures	Mean percent abnormal larvae	Mean PBI	PBI range
1 & 2 (comb.)	0.1 & 3	42	95.9	1,087.8	6–3,840
3	5	9	67.8	105.0	1–222
11	7	15	72.2	70.2	4–250
4	8	15	44.2	26.8	1–91
5	12	12	27.5	10.1	1–25
10	16	21	19.5	12.3	2–35
6	17	21	17.8	3.7	0–22
9	18	21	16.1	14.0	0–28
8	19	15	23.3	3.2	1–7
7	20	15	22.9	3.6	0–9

restrial PBI, and salinity concentration. Chlorophyll *a* is measured in the raw samples only.

Raw, unadjusted bioassay results for the first seven months are shown in Table 2. It is apparent that larval abnormalities increased with the decreasing distance from the pollution source, with all stations within 8 km showing abnormalities of 44 percent or greater. Similarly, high PBI and high abnormalities go together, which suggests a toxic influence of SWL from the Bellingham mill.

Long-term, *in situ* bioassays with seed stages and adult oysters are conducted at six locations (Fig. 4) to determine mortalities, growth rate, and condition index (Westley, 1959). When this program was initiated in June, 1963, the oysters were held in asphaltum-coated metal mesh baskets supported in 2.4 × 3 m anchored rafts. Test populations consisted of 50 pieces of seed cultch, 150 one-year-old and 100 two-year-old Pacific oysters. It was discovered shortly that violent tossing of the rafts in the open sweep of water during stormy weather caused the oysters to grind together, interrupted their feeding, and raised questions concerning other aspects of the test conditions.

The limited condition index data available at this point were sufficiently promising to justify continuing and improving the program. The first modification was to stabilize each raft by attaching two 35-foot-long Douglas fir saw logs in the manner of trailing rudders. Next, 4,000 test oysters were cemented with calcium aluminate and Portland cement to Fiberglas panels suspended vertically from the rafts 1 m deep at panel midpoint. It is now possible to remove each panel from the water for periodic examination and photographing. Oyster growth can be measured on the photograph by planimeter, and the growth history of each specimen can be followed individually. Quarterly, a sample consisting of 25 oysters on a panel will be taken to the laboratory to determine the

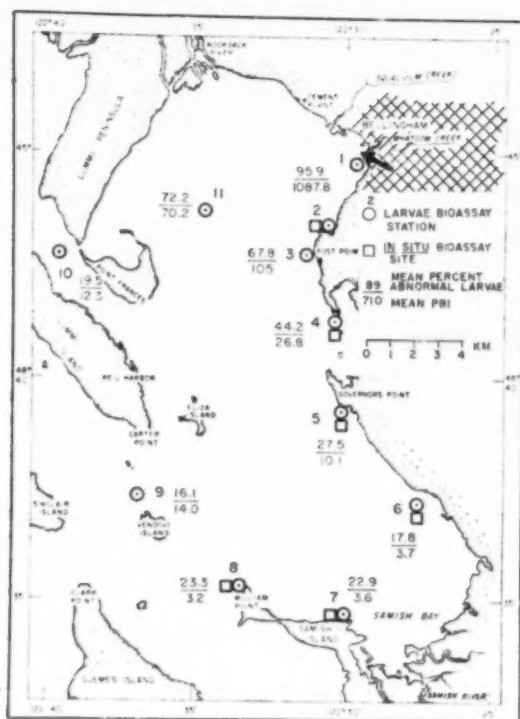


Fig. 4. Bellingham, Washington. Sampling stations for oyster larva bioassays and sites for *in situ* bioassays, May–October, 1963.



Fig. 5. Everett, Washington. Average surface PBI, May, 1962-May, 1963.

condition index. No data are yet available because the program was not revised until March of 1964.

OBSERVATIONS IN THE EVERETT AREA

OCEANOGRAPHIC

The City of Everett, located on Port Gardner at the mouth of the Snohomish River, is the site of two large sulfite pulp and paper mills (Fig. 5). Because of a thin freshwater layer at the top, surface effluents do not mix downward past the halocline. The bulk of the SWL from these mills is released through a deep diffuser, reported to be 91 m at its upper end and 104 m at its lower end. This being the case, there is an initial upward plume displacement of about 25 m, since the peak PBI is usually found at 75 m over the diffuser and at distance from it. The plume depth has been found to layer out at 50 m on occasion. Diurnal station data for the Everett area are not yet available, and significant variation in plume depth may occur over a tidal cycle.

Tides in the area under study are mixed and the mean diurnal range is 3.4 m. The tidal currents are described by the U. S. Coast and Geodetic Survey (1952) as "weak and variable", and the net current direction is northward along the bottom from Possession Sound. Considerable dilution of surface waters

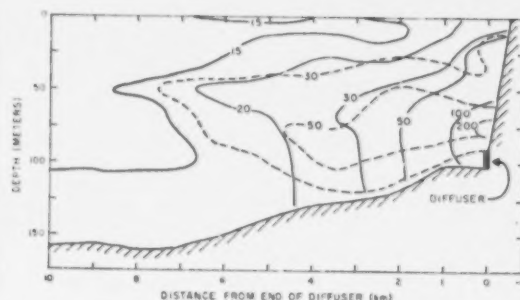


Fig. 6. Everett, Washington. Vertical section of PBI (ppm). Averaged for May, 1962-May, 1963 (solid lines) and for August 3, 1962 (dashed lines), diffuser to Saratoga Passage.

occurs because of precipitation and entry of the Snohomish River; net motion of surface waters is south. Sills are present where Possession Sound joins Port Susan. Their effect on water exchange with Port Susan and on oxygen consumption therein has been described by Barnes and Collias (1958). Since 1952, numerous hydrographic stations have been occupied in Possession Sound and adjacent areas by the University of Washington, which also operates a hydraulic model of Puget Sound, including the Everett area (Barnes *et al.*, 1954).

From May, 1962, hydrographic stations were occupied monthly at about one nautical mile intervals radially from the end of the deeper diffuser. Water samples for temperature, salinity, DO, PBI, and pH were collected by Nansen bottle at 0, 5, 10, 20, 30, 50, 75, 100, 125, and 150 m, depth permitting. Eleven cruises were completed from May, 1962, through May, 1963. Average surface PBI for this period is shown in Figure 5. There is a gradient of PBI directed into the inner harbor where surface outfalls are located. Concentrations of 10 ppm occur throughout the Everett area and in the entire Port Susan region.

Figure 6 shows a vertical section of PBI from the diffuser into Saratoga Passage. Indicated here are the

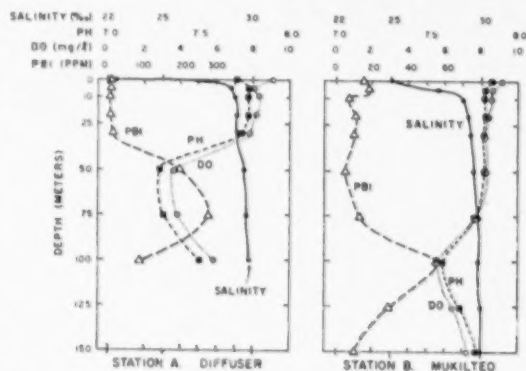


Fig. 7. Everett, Washington. Station curves, April 16, 1963.

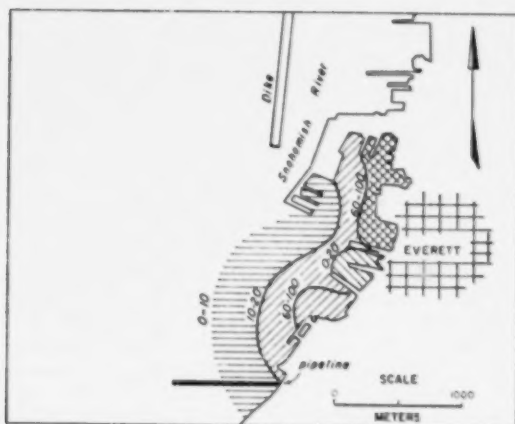


Fig. 8. Everett, Washington. Zones of toxicity to juvenile salmon as percentage of mortality in 24 hours. Composite of six tests.

11-cruise average PBI values and a single cruise (August, 1962) observation showing the 30 and 50 ppm contours only. This representation is somewhat analogous to the average and instantaneous configurations found in industrial smokestack meteorological studies (Pasquill, 1962).

The effect of SWL on DO concentrations and pH is illustrated in Figure 7. The data shown were obtained on April 16, 1963, and are typical of the consistent image effect correlation between SWL, pH, and DO. The station over the diffuser shows the more drastic reduction in DO and pH, as would be expected; the Mukilteo Station is 7.2 km distant from the pipeline, yet the effect of wastes is still present although at a greater depth than that of the station over the diffuser.

JUVENILE SALMONIDS

In the vicinity of Everett, the Snohomish River is used as a spawning stream by four species of salmon (*Oncorhynchus tshawytscha*, *O. kisutch*, *O. keta*, *O. gorbuscha*) and steelhead trout (*Salmo gairdnerii*). In addition, the adjacent waters of Port Gardner Bay, into which the river empties, are used as nursery and feeding grounds by juvenile salmonids and by bottom fish and crabs. The salmon, steelhead, and crab fishery of this area had an estimated 1962 commercial and sport harvest worth \$979,949.

The environmental conditions in the area are alarming because juvenile salmonids from the river have been found to invade waterfront areas where water quality conditions are known to be poor. Live box bioassays with juvenile chum salmon (*O. keta*) were made at 23 stations in this area. They revealed that environmental conditions were at times lethal to the test fish populations, as shown in Figure 8. On these occasions, temperature, salinity, and PBI were not at levels expected to be lethal. When mortalities occurred, they coincided with free chlorine concentra-

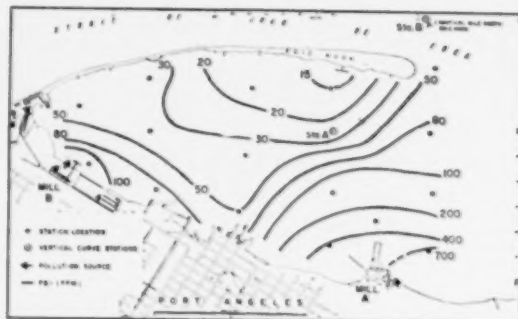


Fig. 9. Port Angeles, Washington. Average surface PBI, November, 1962-December, 1963.

tions of up to 50 ppm, pH below 6.5, sulfide concentrations of 0.5 ppm, or DO concentrations approaching zero. Fortunately, new waste-handling facilities now being provided by the mills will help eliminate these adverse waterfront conditions.

OBSERVATIONS IN THE PORT ANGELES AREA

OCEANOGRAPHIC

A 14-cruise average of surface PBI for November, 1962, through December, 1963, is shown in Figure 9. Two PBI sources are immediately apparent: a pulp and paper mill at the west end of the harbor, and another at the southeast. These are essentially point sources with fluctuating discharges.

On September 8, 1963, the PBI near the outfall of Mill A was greater than 3,500 ppm (Fig. 10). A Secchi disk reading one mile north of Ediz Point was 13.0 m, the highest obtained in this study. Contours of PBI at irregularly spaced concentrations and Secchi disk readings at 3-m contours show considerable agreement. Light penetration, as estimated by Secchi disk, has been reduced by 10 m in the immediate vicinity of both mills and by 4 m over most of the harbor. This is in contrast with the situation on August 30, 1963 (Fig. 11), when Mill A had been

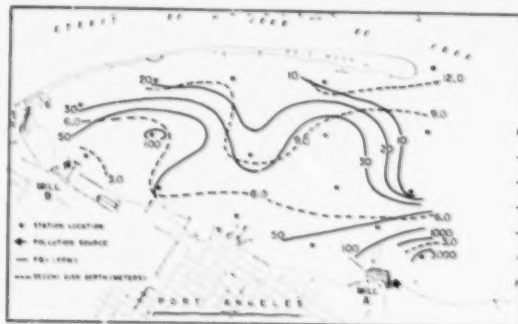


Fig. 10. Port Angeles, Washington. Surface PBI and Secchi disk depth, September 8, 1963.

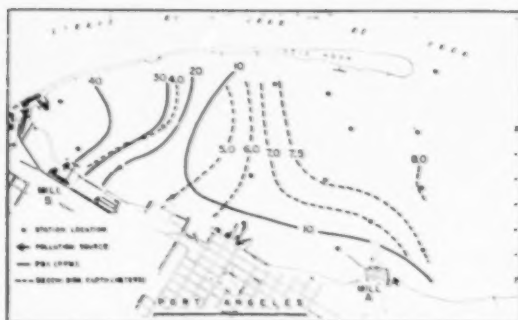


Fig. 11. Port Angeles, Washington. Surface PBI and Secchi disk depth, August 30, 1963.

shut down for a period of 11 days and the only PBI source was Mill B. Although the Secchi disk reading in the Strait was 8.0 m, concurrent with a plankton bloom, the only effect on light penetration was localized in the west end of the harbor; sharply reduced PBI was also noted throughout the harbor.

Station curves for Port Angeles Harbor (Station A) and the Strait of Juan de Fuca (Station B, one nautical mile due north of Ediz Hook Point) are shown in Figure 12. PBI values in the Strait of 2 ppm and less are background readings; this station is completely unaffected by mill wastes. There is a steady increase of salinity with depth to a maximum of 32.1 ‰ at 70 m and a decrease in pH and DO. In the harbor, PBI decreases from 50 ppm at the surface to 2 ppm at the bottom in 20 m of water. Surface salinity in the harbor is about 4 ‰ less than in the strait. There is no sharp halocline, as at Everett and Bellingham, and the PBI versus depth curves usually reflect this by decreasing more regularly in the top few meters.

OYSTER STUDIES

Oyster larva bioassays similar to those described

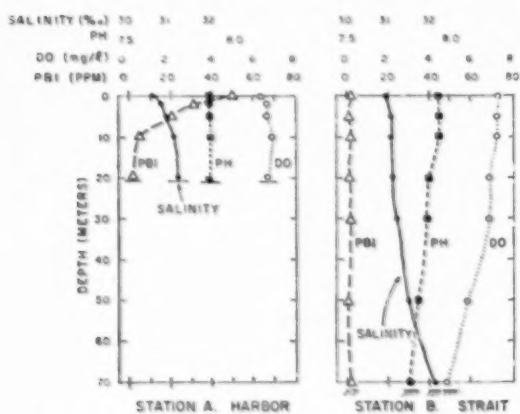


Fig. 12. Port Angeles, Washington. Station curves, October 29, 1963.

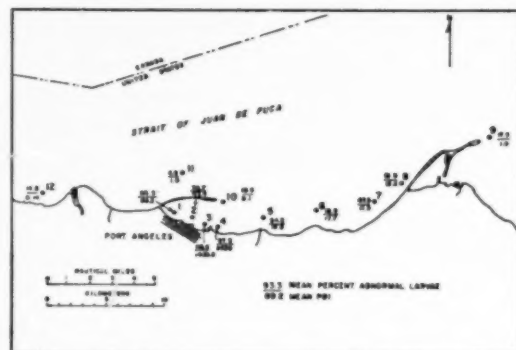


Fig. 13. Port Angeles, Washington. Stations for oyster larva bioassay samples.

for the Bellingham-Samish area also have been made at Port Angeles. Once each month, samples are collected by seaplane from 12 stations (Fig. 13), delivered to the laboratory, and processed in the same manner as the Bellingham-Samish samples.

Preliminary unadjusted results for the first seven months are shown in Table 3. Here, as at other pulp mill sites, larval abnormalities increase as distance to the waste source decreases.

SUMMARY

In situ studies of pulp and paper mill waste pollution, such as those in progress in Puget Sound and the Strait of Juan de Fuca, require the closely coordinated efforts of oceanographers, biologists, engineers, and others. Studies on the adverse effects of SWL and other mill wastes, carried out solely in the laboratory, do not sufficiently simulate field conditions and, therefore, cannot be projected directly to existing conditions in the marine environment. Hence, several "bioassay" techniques are used. They vary from di-

Table 3. Oyster larva bioassay data for Port Angeles Harbor and the Strait of Juan de Fuca. Summary for period, May 13 to November 20, 1963.

Station	Kilo-meters from pollution source	Number of cultures	Mean percent abnormal larvae	Mean PBI	PBI range
1	In harbor	21	93.3	89.2	19-420
2	In harbor	21	70.7	55.4	5-186
3	In harbor	21	98.6	1,429.8	23-14,750
4	In harbor	21	97.5	3,520.0	190-7,200
5	4 east	6	54.2	19.0	1-37
6	9 east	21	61.8	17.7	10-27
7	14 east	6	47.6	11.5	9-14
8	16 east	6	51.5	13.5	5-22
9	25 northeast	6	17.9	1.0	0-1
10	2 north	21	18.5	8.1	0-37
11	7 northwest	18	4.6	1.0	0-3
12	18 west	21	14.5*	0.14	0-1

* 100 percent mortality on one trip due to low salinity. Elimination of this sample puts mean percent abnormal larvae at 1.6.

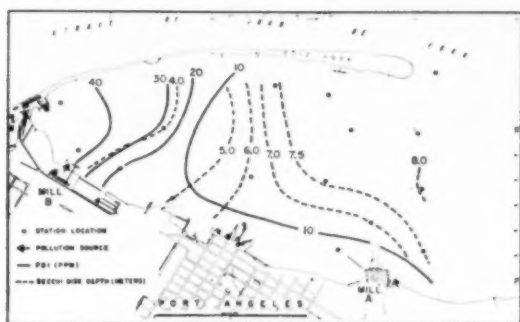


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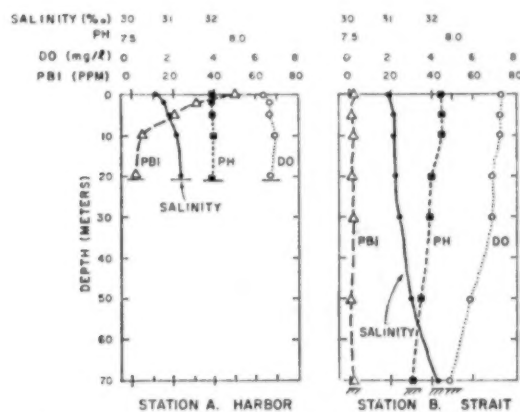


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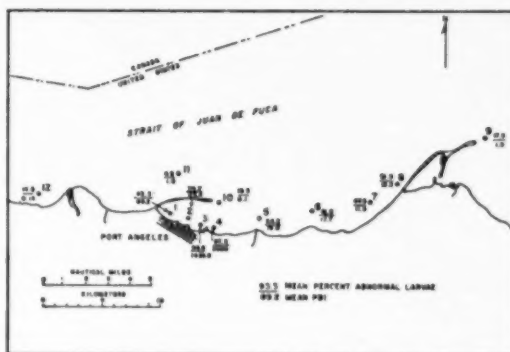


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4	In harbor	21	97.5	3,520.0	190-7,200
5	4 east	6	54.2	19.0	1-37
6	9 east	21	61.8	17.7	10-27
7	14 east	6	47.6	11.5	9-14
8	16 east	6	31.5	13.5	5-22
9	25 northeast	6	17.9	1.0	0-1
10	2 north	21	18.5	8.1	0-37
11	7 northwest	18	4.6	1.0	0-3
12	18 west	21	14.5*	0.14	0-1

* 100 percent mortality on one trip due to low salinity. Elimination of this sample puts mean percent abnormal larvae at 1.6.

rect examination of marine populations and the influence of pollutants on them, and semi-natural *in situ* bioassays with maturing oysters, to laboratory bioassays with oyster larvae to test water collected at suspect points.

Oceanographic studies have traced the distribution and persistence of mill wastes. They also show that the wastes occur at points where oysters and juvenile salmon are of major concern. Although still incomplete, the bioassays with growth stages of salmon and oysters cast doubts on suitability of habitat near the waste sources.

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